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Fluid inclusion study on the wells MT-1 and MT-2 in the Mataloko geothermal system, Indonesia

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Abstract: Fluid inclusions from the wells MT-1 and MT-2 in the Mataloko geothermal system were studied microthermometrically and geochemically. The microthermometric data show that homogenization temperatures of the fluid inclusions at the bottom of the well MT-1 are concordant to the thermal structure estimated from other geological and geochemical data of Mataloko. However, those at the bottom of the well MT-2 are 20-30 ℃ higher than the estimated present temperature (200 ℃). Salinities of all the fluid inclusions are very low. Semi-quantitative gas analysis for fluid inclusions from the bottom of the well MT-1 indicates that the inclusions consist mainly of H_2O with trace amounts of CO_2 and CH_4. These data imply that the fluid inclusions were probably formed by trapping steam-condensed water at 220-235 ℃ with small amounts of the gases at a shallow level in the geothermal system. Comparison of the homogenization temperatures to the boiling point curve of water for the well MT-2 suggests that at least 100 m have been eroded from the Mataloko area since the geothermal activity began.

1. Introduction

Geothermal exploration wells MT-1 and MT-2 were drilled in the Mataloko geothermal system, 10 km southeast of Bajawa on Flores Island, Indonesia (Muraoka *et al.*, 1998; Fig. 1), in the "Research Co-operation Project on the Exploration of Small-Scale Geothermal Resources in the Eastern Part of Indonesia" in order to confirm the geothermal model of Mataloko (WEST JEC and MRC, 2001). Borehole temperatures were measured in the well MT-2 just after drilling, but there was no temperature data for the well MT-1 (WEST JEC and MRC, 2001).

The authors microthermometrically and geochemically studied the fluid inclusions in rock cuttings recovered from the wells. This paper preliminarily reports the temperature and geochemistry of geothermal fluids in the Mataloko area.

2. Geology of the boreholes and sample description

Muraoka *et al.* (2000), Nasution *et al.* (2000), Takahashi *et al.* (2000) and WEST JEC and MRC (2001) reported the general geology, alteration and properties of geothermal fluids in the Mataloko area. The area is covered with volcanic rocks (e.g. andesite-basalt lava, andesitic pyroclastic rocks) of Neogene-Quaternary, and there are many high-temperature (over 77-89 ℃) hot springs. The wells MT-1 and MT-2 penetrate the volcanic rocks, and

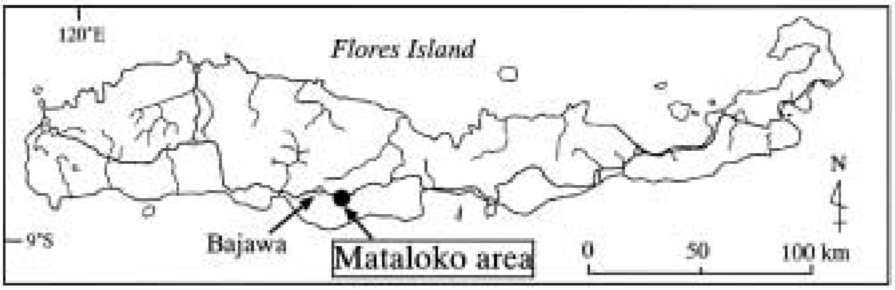

Fig. 1 Locality of the Mataloko geothermal area on Flores Island, Indonesia.

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Keywords: fluid inclusion, microthermometry, gas analysis, borehole temperature

their depths are 207 m and 162 m, respectively. The volcanic rocks in the wells are hydrothermally altered in some places. The X-ray diffraction analyses for rock cuttings recovered from the wells indicated sporadic occurrences of wairakite with montmorillonite and chlorite/montmorillonite mixed layer minerals, and the alteration minerals are possibly formed through high-temperature hydrothermal alteration above 200 ℃. However, vapor is presently dominant at the levels where the hydrothermal alteration minerals occur, and the minerals might have been produced during a past alteration stage rather than in the present hydrothermal activity. Discharged fluids from the wells are separated from the vapor-dominant fluid that originated from heated meteoric water. Chemical analysis of the discharged fluid shows that the gas content of the fluid is 0.20-0.45 vol.% for MT-1 and 0.26-0.29 vol.% for MT-2. CO_2 is the main component (about 90 vol.%) in the non-condensable gases with small amounts of H_2S, N_2, H_2, CH_4, Ar and He, although CH_4 and He were not measured for the fluid from MT-1. The gas components were possibly derived from magmatic volatile or attributed to water-rock interaction at high temperatures. WEST JEC and MRC (2001) shows that geothermometers of gas ratios and isotopes for the discharged fluid from MT-2 indicate 232-343 ℃. The temperature at the bottom of MT-2 is estimated to be 200 ℃, and 230 ℃ at slightly deeper part than the bottom based on an analysis on a physical property of the discharged fluid, distribution of the alteration minerals and gas geothermometers (WEST JEC and MRC, 2001).

The studied samples were quartz and calcite, which commonly contain fluid inclusions, in the cuttings from the altered zones in the wells: quartz from the 205-207 m depth of MT-1 and the 156-159 m depth of MT-2, and calcite from the 135-138 m and 153-156 m depths of MT-2 were used for microthermometry. Quartz from the 205-207 m depth of MT-1 was also used for gas analysis of fluid inclusions in order to reveal the geochemistry of the fluid in the geothermal system. The cuttings were smaller than several millimeters in size, and occurrences and paragenesis of the individual minerals were not clear in detail. However, the studied quartz and calcite were probably formed hydrothermally because the host volcanic rocks seldom include these minerals primarily.

Secondary inclusions were observed in all the samples, and primary inclusions were in quartz. All of the fluid inclusions were two-phase vapor-rich and liquid-rich without daughter minerals. Vapor-rich inclusions are dominant in every sample and often form exclusive arrays of secondary inclusions with a small number of liquid-rich inclusions.

3. Measurement of the fluid inclusions

3.1. Microthermometry

Homogenization temperatures (*Th*) and final melting points of ice (*Tm*) of the fluid inclusions were measured by a USGS-type gas-flow heating/freezing stage at the National Institute of Advanced Industrial Science and Technology, Japan (AIST). For the measurement, fragments of the cuttings and hydrothermal minerals were bound with epoxide resin, thinned and polished. The total uncertainties of heating and freezing runs are estimated to be ±3 ℃ and ±0.2 ℃, respectively (Sawaki and Sasada, 1990). Results of the measurements are shown in Figs. 2, 3 and 4.

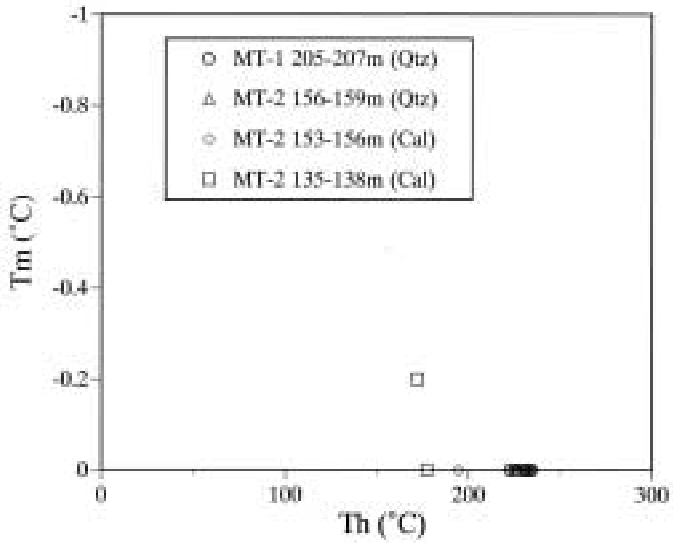

Fig. 2 Final melting points of ice (Tm) vs. homogenization temperatures (Th) of fluid inclusions in quartz (Qtz) and calcite (Cal).

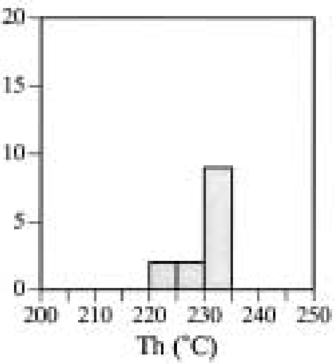

Fig. 3 Histogram of homogenization temperatures (Th) of fluid inclusions in quartz from the 205-207 m depth (bottom) of the well MT-1.

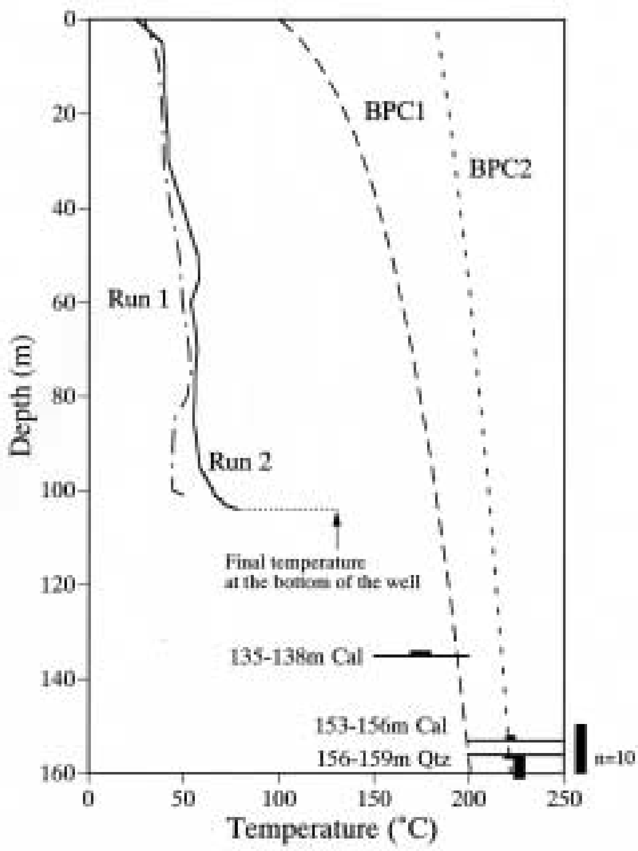

Fig. 4 Borehole temperatures and histograms of homogenization temperatures of fluid inclusions in quartz (Qtz) and calcite (Cal) for the well MT-2. Borehole temperatures of MT-2 (Runs 1 and 2) are after WEST JEC and MRC (2001). The BPC1 and BPC2 are the boiling point curves of water with depths adjusted to 100 ℃ at the present surface and 100 m above the present surface, respectively.

Figure 2 shows that *Tm* of the fluid inclusions are nearly equal to zero except one: *Tm* of -0.2 ℃ equals to 0.35 wt.% NaCl eq. (Bodnar and Vityk, 1994). Figure 3 indicates that *Th* of the fluid inclusions at the bottom of MT-1 range from 220 to 235 ℃, especially concentrated in the 230-235 ℃ range. Figure 4 shows *Th* histograms of the fluid inclusions with the boiling point curves of water adjusted to 100 ℃ at the present surface (BPC1) and to 100 ℃ at 100 m higher than the present surface (BPC2). The *Th* at the bottom of MT-2 are 20-30 ℃ higher than the estimated temperature (200 ℃; WEST JEC and MRC, 2001) and BPC1, and are plotted near BPC2.

3.2. Gas analysis

Gases of the fluid inclusions were analyzed with a gas analytical system of a quadrupole mass spectrometer at AIST (Sasada *et al.*, 1992). For the analysis, minerals such as carbonate and zeolite that are thermally decomposed cannot be used because they produce a large amount of volatile by their decomposition. In cutting samples, only relatively large quartz crystals from the 205-207 m depth of the well MT-1 were available for the analysis. However, the amount of the collected quartz crystals was not enough for bulk analysis, and only a semi-quantitative analysis for individual fluid inclusions (Sasada *et al.*, 1992) was performed. The sample was rinsed with conc-HCl and H_2O_2 to eliminate contamination.

The analytical result is shown in Fig. 5. The data reveal that H_2O is the main component of the fluid inclusions, and trace amounts of CO_2 and CH_4 are detected at a large burst of a fluid inclusion.

4. Properties of the inclusion fluid

The *Th* data of the fluid inclusions (Figs. 3 and 4) suggest that borehole temperatures at the bottom of the wells MT-1 and MT-2 are 220-235 ℃. The data of MT-1 are concordant with the estimated thermal structure (WEST JEC and MRC, 2001). However, Fig. 4 shows that *Th* data of the bottom of MT-2 are 20-30 ℃ higher than the estimated temperature, 200 ℃ (WEST JEC and MRC, 2001) and BPC1 at the bottom of MT-2. The *Th* data are plotted near the boiling point curve of water adjusted to 100 m above the present surface. This suggests that the Mataloko area has been possibly eroded by at least 100 m since the hydrothermal activity began. The fluid inclusions at the bottom of MT-2 might have been formed at a past alteration stage when wairakite and associated clay minerals were produced (WEST JEC and MRC, 2001) before the remarkable erosion. On the other hand, the fluid inclusions at the 135-138 m depth of MT-2 are presumably formed in the present hydrothermal activity.

The present discharged fluids from the wells probably originate from a condensed vapor-dominant fluid in a shallow reservoir of Mataloko (WEST JEC and MRC, 2001). Salinity of the present geothermal fluid in the reservoir is not evaluated, but it is generally expected to be very low in steam-condensed water. The low-salinity (0-0.35 wt.% NaCl eq.) of the fluid inclusions, especially from MT-1, proves that the geothermal fluid in the reservoir is of low-salinity and originates from the condensation of vapor. The discharged fluids from the wells contain CO_2, H_2S, N_2, H_2, CH_4, Ar and He (WEST JEC and MRC, 2001). The individual fluid inclusion analysis (Fig. 5) shows that the fluid inclusions trapped small amounts of CO_2 and CH_4 among the gases. The gas and Tm data suggest that the gas content of the geothermal fluid is also low.

5. Summary

Fluid inclusions from the wells MT-1 and MT-2 in the Mataloko geothermal system were studied micro-

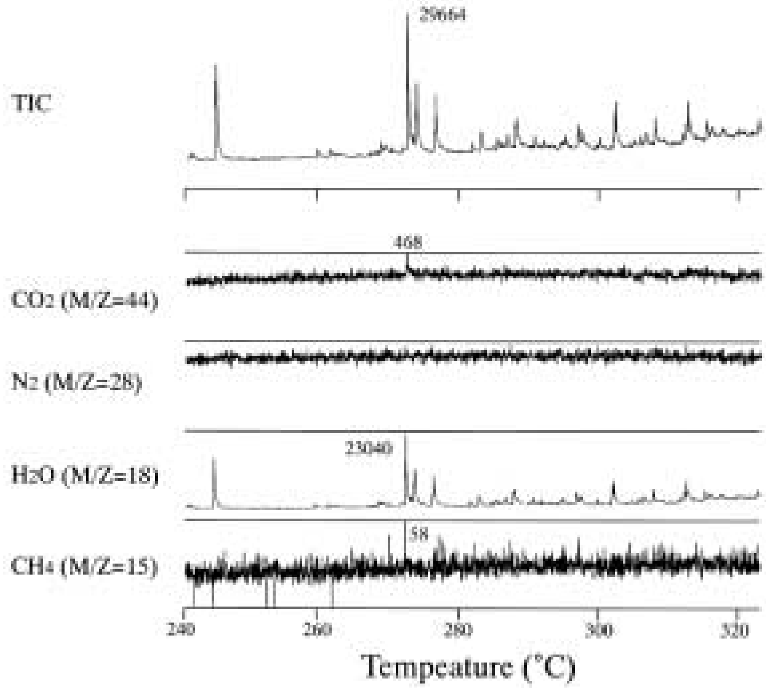

Fig. 5 Result of an individual fluid inclusion analysis for quartz from the 205-207 m depth (bottom) of the well MT-1.
A peak corresponds to decrepitation of a fluid inclusion. The uppermost chart shows total ion current (TIC) detected by the mass spectrometer. The other charts show the mass spectrometer response at mass/electron charge ratio (M/Z)=44 for CO_2, at 28 for N_2, at 18 for H_2O and at 15 for CH_4 as a mass fragment of CH_3. Heating rate is 10 ℃/min. Numbers with the highest peaks (e.g., 29664 in the TIC chart) indicate maximum ion counts.

thermometrically and geochemically. The *Th* data of the fluid inclusions of MT-1 show that temperatures at its bottom are 220-235 ℃. On the other hand, those at the bottom of MT-2 suggest that the Mataloko area has been possibly eroded by at least 100 m, and the fluid inclusions might have been formed at the high-temperature alteration before the erosion. Low salinities of the fluid inclusions imply the present geothermal fluid is of low-salinity and derives from a vapor-condensate at the shallow levels. Semi-quantitative gas analysis and *Tm* data for the fluid inclusions suggest a low gas content of the geothermal fluid in the reservoir.

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インドネシア・マタロコ地熱系の MT-1 及び MT-2 井から得られた流体包有物の研究

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要　旨

マタロコ地熱系の MT-1 及び MT-2 井から得られた流体包有物について，マイクロサーモメトリー及び化学分析を行った．MT-1 井坑底部の流体包有物の均質化温度は，マタロコ地域の地質学的・地球化学的データから推定されている温度構造と一致する．しかし，MT-2 井坑底部の均質化温度データは，推定されている坑底温度（200 ℃）よりも 20 - 30 ℃ 程度高い．全ての流体包有物の塩濃度は低い．MT-1 井坑底から得られた流体包有物についてのガス成分の半定量分析によれば，流体包有物の主成分は H_2O であり，微量の CO_2 と CH_4 を伴う．これらのデータは，流体包有物が，本地熱系の浅部で，少量のガスを含む 220 - 235 ℃ の凝縮水から形成されたことを示している．また，MT-2 井に関しての，均質化温度と水の沸騰曲線の比較から，地熱活動開始以降，本地域が少なくとも 100 m 程度の浸食を被った可能性が示唆される．